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GLOBULAR CLUSTER AGES AND THE FORMATION OF THE GALACTIC HALO

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ABSTRACT

Main-sequence turnoff magnitudes from the recent set of Yale isochrones published by Chaboyer et al. in 1995 have been combined with a variety of relations for the absolute magnitude of RR Lyrae stars [M_v(RR)] to calibrate age as a function of the difference in magnitude between the main-sequence turnoff and the horizontal branch ($\Delta V_{\rm HB}^{\rm TO}$). A best estimate for the calibration of M_v(RR) is derived from a survey of the current literature: $M_v({\rm RR}) = 0.20[{\rm Fe/H}] + 0.98$. This estimate, together with other calibrations (with slopes ranging from 0.15 to 0.30), has been used to derive $\Delta V_{\rm HB}^{\rm TO}$ ages for 43 Galactic globular clusters. Independent of the choice of M_v(RR), there is no strong evidence for an age–Galactocentric distance relationship among the 43 globular clusters. However, an age-metallicity relation exists, with the metal-poor clusters being the oldest. A study of the age distribution reveals that an age range of 5 Gyr exists among the bulk of the globular clusters. In addition, about 10% of the sample are substantially younger, and including them in the analysis increases the age range to 9 Gyr. Once again, these statements are independent of the M_v(RR) relation. Evidence for age being the second parameter governing horizontal-branch morphology is found by comparing the average $\Delta V_{\rm HB}^{\rm TO}$ age of the second parameter clusters to the normal clusters. The second parameter clusters are found to be on average 2–3 Gyr younger than the other clusters, which is consistent with age being the second parameter. These results suggest that globular clusters were formed over an extended period of time, with progressively more metal-rich globular clusters ([Fe/H] $\gtrsim -1.7$) being formed at later times.

Subject headings: Galaxy: formation — Galaxy: halo — globular clusters: general — Hertzsprung-Russell diagram — stars: evolution — stars: interiors

1. INTRODUCTION

Understanding the process of galaxy formation continues to be one of the key quests in astrophysics. In this regard, the Milky Way plays a unique role because it is the only galaxy for which we can obtain detailed chemical, kinematic, and chronological information. Observational and theoretical studies over the last 60 years have led to a basic understanding of how the Galaxy formed (see Larson 1991). It is clear that the spherical, metal-poor halo of our Galaxy formed early during the collapse of the proto-Galactic cloud. The collision at the midplane halted the gas collapse and led to the formation of the rotating, thin disk.

However, there are many unanswered questions regarding the formation of the Galaxy. When did the bulge form? How and when did the thick disk form? How important is later infall and accretion? Did the halo form over an extended period of time? Was halo formation a chaotic or smooth process? An important step toward answering these questions is to determine accurate ages for the various stellar populations. Globular clusters (GCs) play a key role in this regard because their derived ages are the most accurate of any object in the halo and thick disk/bulge. In this paper, ages for 43 Galactic GCs that have well-observed color-magnitude diagrams (CMDs) are derived and analyzed to probe the formation of the Galactic halo.

Information regarding the formation and evolution of the Galaxy has traditionally been obtained by surveys of stars or star clusters that have one or more of the following properties measured: locations, metallicities, velocities, and ages. The classic paper by Eggen, Lynden-Bell, & Sandage (1962) analyzed ultraviolet excesses, radial velocities, and proper motions of nearby stars to conclude that the Galactic halo formed during the rapid, monolithic collapse of the proto-Galactic gas cloud. Evidence for a quite different halo formation theory was presented by Searle & Zinn (1978). On the basis of their studies of GC metallicities and horizontal-branch morphology, Searle & Zinn (1978) proposed that the halo formed via accretion over several gigayears (Gyr) in a rather chaotic manner. These contrasting theories continue to be a critical part of discussions of Galactic formation (see Majewski 1993 for a recent review). In this regard, the determination of accurate absolute and relative ages for GCs plays an important role in discovering the timescale for the formation of the Galactic halo.

There are a variety of different methods that can be used to derive the ages of GCs. All of these techniques rely on comparing some aspect of an observed CMD to theoretical stellar models or isochrones. The most accurate relative ages can be derived using the difference in color between the main-sequence turnoff and the base of the red giant branch

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[$\Delta(B-V)$; Sarajedini & Demarque 1990 and VandenBerg, Bolte, & Stetson 1990]. However, the colors of theoretical isochrones are very uncertain, as they depend on stellar atmospheres and the mixing-length treatment of convection. As such, transforming an observed difference in $\Delta(B-V)$ into an age difference is subject to large theoretical uncertainties. These uncertainties can be minimized by comparing clusters with similar metallicities.

If one wishes to intercompare ages of clusters with different metallicities, then the difference in magnitude between the main-sequence turnoff and the horizontal branch ($\Delta V_{\rm HB}^{\rm TO}$) yields ages that have the smallest theoretical errors. Unfortunately, it is often difficult to determine $\Delta V_{\rm HB}^{\rm TO}$ observationally, so that the error in the derived age can be rather large ($\sim 10\%$). The absolute magnitude of the main-sequence turnoff [M_v(TO)] is a well-determined theoretical quantity. The new set of Yale isochrones (Chaboyer et al. 1995) provides an up-to-date calibration of M_v(TO) for a wide range of ages and chemical compositions. The absolute magnitude of the horizontal branch (HB) is independent of age (over the range $\sim$8–22 Gyr); however, its absolute level is not well determined in theoretical models because of the importance of convection and semi-convection in the nuclear burning regions of these stars. Fortunately, there are a variety of independent, observationally based methods that can be used to determine the absolute magnitude of RR Lyr stars [M_v(RR)] that lie on the HB. Hence, the $\Delta V_{\rm HB}^{\rm TO}$ ages derived in this paper are based on the calibration of M_v(TO) as a function of age and metallicity from the new set of Yale isochrones, coupled with a variety of determinations of M_v(RR).

There have been a number of studies of the $\Delta V_{\rm HB}^{\rm TO}$ ages of GCs in recent years (Sarajedini & King 1989; Sandage & Cacciari 1990; Carney, Storm, & Jones 1992; Chaboyer, Sarajedini, & Demarque 1992; Walker 1992a; Caputo et al. 1993; Sandage 1993). These studies have shown that the choice of a M_v(RR) relation is crucial to the conclusions that are drawn based on $\Delta V_{\rm HB}^{\rm TO}$ ages. This work differs from previous studies in three main ways: (1) use of the new Yale isochrones to determine M_v(TO); (2) an expanded observational database of observed $\Delta V_{\rm HB}^{\rm TO}$ values (30% more than in our 1992 compilation); and (3) the use of a large number of M_v(RR) relations to explore in detail how the choice of M_v(RR) affects our conclusions.

A brief description of the new Yale isochrones along with a discussion of M_v(RR) and the theoretical calibration of $\Delta V_{\rm HB}^{\rm TO}$ is presented in § 2. Section 3 reviews the basic observational data and tabulates the $\Delta V_{\rm HB}^{\rm TO}$ ages. A discussion of the correlations between age, metallicity, and galactocentric distance is contained in § 4. Evidence for an age range within the Galactic globular cluster system is presented in § 5. Section 6 examines the second parameter problem in the context of the $\Delta V_{\rm HB}^{\rm TO}$ ages. Finally, § 7 discusses the major results of this paper and their implications for the formation of the Galactic halo.

2. THEORETICAL CALIBRATION OF $\Delta V_{\rm HB}^{\rm TO}$

2.1. M_v(TO)

The recent set of Yale isochrones (Chaboyer et al. 1995) is used to provide a calibration of M_v(TO) as a function of age and metal abundance. These isochrones are based on new stellar evolution models that incorporate the latest available input physics: opacities from Iglesias & Rogers (1991, high temperature) and Kurucz (1991, low temperature), and nuclear reaction rates from Bahcall & Pinsonneault (1992) and Bahcall (1989). The color transformation of Green, Demarque, & King (1987) was used to construct isochrones in the observational plane. The new set of Yale isochrones is based on standard stellar models, which do not include the effects of diffusion or the Debye-Hückel correction to the equation of state. Including these two effects would systematically reduce the GC ages presented in Table 3 by $\sim 13\%$ (Chaboyer 1995).

In order to span the range of metallicities of observed globular clusters, M_v(TO) values were determined from isochrones with [Fe/H] $= -2.8$, -2.3, -1.8, -1.3, -1.0, and -0.44. The isochrones with [Fe/H] ≤ -1.0 have a helium abundance of $Y = 0.23$. This is in good agreement with recent determinations of the primordial helium abundance (Pagel & Kazlauskas 1992; Balbes, Boyd, & Mathews 1993; Izotov, Thuan, & Lipovetsky 1994). The most metal-rich isochrone ([Fe/H] $= -0.44$) has a helium abundance of $Y = 0.25$ and assumes that the α-capture elements (O, Mg, Si, S, and Ca) are enhanced by 0.2 dex over their solar values (i.e., [α/Fe] $= +0.2$). The more metal-poor isochrones assume [α/Fe] $= +0.4$. These [α/Fe] values were chosen to be in agreement with observations of halo stars (Lambert 1989; Dickens et al. 1991; King 1994; Nissen et al. 1994). The new Yale isochrones are tabulated every 2 Gyr for the older ages (10–22 Gyr). In order to provide a finer grid for interpolation purposes in this study, we have recomputed these isochrones using a 1 Gyr spacing, between 8 and 22 Gyr.

2.2. M_v(RR)

There are numerous observational and theoretical techniques that may be used to derive M_v(RR). There is general agreement that the absolute magnitude of RR Lyr stars is given by an equation of the form

$$M_v({\rm RR}) = \mu[{\rm Fe/H}] + \gamma \, , \quad (1)$$

where μ is the slope with metallicity and γ is the zero point. The zero point is important for setting the overall absolute ages, while the slope is important in determining the relative ages for GCs with different metallicities. Some techniques for determining M_v(RR) are best for determining the zero point, while other techniques are best at deriving the slope. Because of possible systematic effects, the Baade-Wesselink and infrared flux analysis are best used to determine the slope with metallicity. Such analyses of field RR Lyr stars have been published recently by two groups. Jones et al. (1992) found $\mu = 0.16 \pm 0.03$, while Skillen et al. (1993) determined $\mu = 0.21 \pm 0.05$. The theoretical HB models of Lee (1990) should also give a reliable determination of the slope and yield $\mu = 0.18 \pm 0.01$. From an analysis of the Oosterhoff period shift effect in GCs, Sandage (1993)[2] found $\mu = 0.30 \pm 0.12$. Thus, it appears that M_v(RR) has a rather shallow slope with metallicity of $\mu \simeq 0.20$, though it may be somewhat premature to exclude totally slopes as high as $\mu = 0.30$.

[2] Sandage (1993) gives an error of 0.12 for the slope of $M_{\rm bol}$(RR) with metallicity but does not quote an error in M_v(RR). However, Sandage obtains M_v(RR) from a simple transformation of his $M_{\rm bol}$(RR) equation ($M_{\rm bol} = M_v + 0.06$[Fe/H] $+ 0.06$), so we have taken the error in his M_v(RR) relation from his quoted error in his $M_{\rm bol}$(RR) relation.

TABLE 1

FITTING COEFFICIENTS

	STANDARD						RED HB					
M_v(RR)	β_0	β_1	β_2	β_3	β_4	β_5	β_0	β_1	β_2	β_3	β_4	β_5
0.17[Fe/H]+0.790......	74.995	−47.943	8.435	6.219	0.551	−2.025	100.913	−62.728	10.550	21.501	3.562	−5.436
0.20[Fe/H]+0.980......	77.703	−51.506	9.419	4.669	0.457	−1.611	88.669	−58.294	10.485	18.692	3.385	−4.810
0.15[Fe/H]+0.980......	83.026	−54.407	9.813	7.659	0.573	−2.664	81.215	−53.656	9.768	22.377	3.664	−6.078
0.15[Fe/H]+0.725......	76.664	−48.252	8.335	7.177	0.614	−2.297	105.035	−64.100	10.550	23.136	3.675	−5.858
0.20[Fe/H]+1.060......	78.270	−52.404	9.725	5.012	0.456	−1.752	69.791	−47.837	9.144	19.122	3.474	−5.006
0.20[Fe/H]+0.820......	72.434	−46.790	8.343	4.684	0.503	−1.499	99.041	−62.095	10.550	19.475	3.408	−4.803
0.25[Fe/H]+1.140......	74.978	−51.177	9.753	2.728	0.406	−0.880	85.981	−57.814	10.783	19.077	3.341	−4.855
0.25[Fe/H]+0.915......	67.189	−44.791	8.296	2.212	0.434	−0.656	93.237	−60.091	10.550	16.014	3.195	−3.748
0.30[Fe/H]+1.220......	72.167	−50.378	9.842	0.000	0.240	0.000	81.425	−56.089	10.783	15.884	3.125	−3.776
0.30[Fe/H]+1.010......	67.561	−45.831	8.638	0.000	0.249	0.000	86.174	−57.216	10.420	12.826	3.024	−2.718

A reliable determination of the zero point in equation (1) can be made by measuring the apparent magnitude of a number of RR Lyr stars in the LMC and then using the distance to the LMC to obtain γ. This is the approach used by Walker (1992a) who found $M_v(\mathrm{RR}) = 0.44 \pm 0.10$ at $[\mathrm{Fe/H}] = -1.9$ (implying $\gamma = 0.82 \pm 0.10$), assuming $(m - M)_{\mathrm{LMC}} = 18.5 \pm 0.10$. This distance modulus to the LMC was based on main-sequence fitting and analysis of the Cepheid variables and the rings associated with SN 1987A. However, Gould (1995) has recently reanalyzed the SN 1987A distance estimate and has determined an upper limit of $(m - M)_{\mathrm{LMC}} = 18.37$. Using this distance estimate to the LMC and Walker's (1992a) RR Lyr photometry, one finds $M_v(\mathrm{RR}) = 0.57$ at $[\mathrm{Fe/H}] = -1.9$ ($\gamma = 0.95$). Using a statistical parallax analysis of field RR Lyr stars, Layden, Hanson, & Hawley (1994) found a zero point that is 0.24 mag fainter ($\gamma = 1.06$) than that quoted by Walker (1992a) (and 0.11 mag fainter than the revised Walker value above). This suggests that $\gamma \simeq 0.98$ is a reasonable choice, and so our best estimate for the absolute magnitude of the RR Lyr stars is $M_v(\mathrm{RR}) = 0.20[\mathrm{Fe/H}] + 0.98$. This choice of M_v(RR) predicts that the RR Lyr stars in M92 (with $[\mathrm{Fe/H}] = -2.24 \pm 0.08$) should have $M_v(\mathrm{RR})_{\mathrm{M92}} = 0.53 \pm 0.02$. In their Baade-Wesselink analysis of M92 RR Lyr stars, Storm et al. (1994) determined $M_v(\mathrm{RR})_{\mathrm{M92}} = 0.43 \pm 0.22$, which is in reasonable agreement. However, the possible 0.1 mag discrepancy would reduce the ages for the metal-poor clusters by 10%, and so a more precise determination of M_v(RR) in metal-poor GCs is clearly desirable. Although we have derived our best estimate for the absolute magnitude of the RR Lyr stars $\{M_v(\mathrm{RR}) = 0.20[\mathrm{Fe/H}] + 0.98\}$, in order to explore in a systematic way the effect that uncertainties in M_v(RR) have on the GC ages, ages will be derived using both the Walker (1992a) and Layden et al. (1994) zero points with slopes that vary from 0.15 to 0.30.

2.3. *Derivation of* $\Delta V_{\mathrm{HB}}^{\mathrm{TO}}$ *Ages*

The M_v(TO) values from the new Yale isochrones are combined with a given M_v(RR) relation to form a grid, which specifies age given $\Delta V_{\mathrm{HB}}^{\mathrm{TO}}$ and [Fe/H]. The grid is then fitted to an equation of the form

$$t_9 = \beta_0 + \beta_1 \Delta V + \beta_2 \Delta V^2 + \beta_3[\mathrm{Fe/H}] + \beta_4[\mathrm{Fe/H}]^2 + \beta_5 \Delta V[\mathrm{Fe/H}] , \qquad (2)$$

where t_9 is the age in Gyr. The rms residuals of the points from the fit were about 0.15 Gyr. The above formula is used to determine ages for GCs that have RR Lyr stars or a blue HB. In the case of clusters with purely blue HBs (i.e., few or no RR Lyrae variables), observers quote the V magnitude of the blue edge of the instability strip, which is usually a reasonably accurate measurement of M_v(RR). In some cases, they compare to the blue HB of a cluster with RR Lyrae stars to infer M_v(RR).

In the case of clusters with red HBs (HB type[3] ≤ -0.8), the situation is slightly more complicated. In these clusters, observers usually quote the mean or median magnitude of the red HB stars. This quantity can be anywhere from 0.05 to 0.2 mag brighter or fainter than the RR Lyr level depending on the cluster metallicity and age. In order to correct for this effect, a semiempirical approach is taken. The offset between the red HB level and RR Lyr level may be determined from theoretical HB models, and this correction can then be applied to the red HB clusters, as discussed by Fullton et al. (1995). As this offset depends on relative quantities in the theoretical models, it should be reasonably reliable. HB models by Lee, Demarque, & Zinn (1987), Dorman (1992), and Castellani, Chieffi, & Pulone (1991) find offsets that agree to within 0.05 mag. The offsets used in this study are derived from HB models kindly provided to us by Lee (1995). Lee constructed synthetic HB models of red HB clusters with a range of ages and abundance from which he has calculated M_V(HB). Given the relation $M_v(\mathrm{RR}) = 0.17[\mathrm{Fe/H}] + 0.79$, which comes from the Lee HB models, the function $\delta = M_V(\text{red HB}) - M_v(\mathrm{RR})$ can be calculated as a function of [Fe/H] and age. For other RR Lyrae luminosity relations, the function δ is used to correct M_v(RR) to M_V(red HB).

The coefficients of the fit (eq. [2]) for the standard and red HB cases are given in Table 1. These coefficients have been tabulated for 10 different M_v(RR) relations: the Lee (1995) relation $\{M_v(\mathrm{RR}) = 0.17[\mathrm{Fe/H}] + 0.79\}$; our best estimate for the true relation $\{M_v(\mathrm{RR}) = 0.20[\mathrm{Fe/H}] + 0.98\}$; and relations with slopes of 0.15, 0.20, 0.25, and 0.30 using the zero points of Walker (1992a) and Layden et al. (1994). These M_v(RR) relations span the range reported by various groups using a variety of observational and theoretical techniques (see § 2.2). The coefficients presented in Table 1 are valid for $-2.8 \leq [\mathrm{Fe/H}] \leq -0.44$ and for ages in the range 8–22 Gyr.

[3] The HB type has the following definition: HB type $\equiv (B - R)/(B + V + R)$, where B is the number of HB stars blueward of the instability strip, R is the number of HB stars redward of the instability strip, and V is the number of RR Lyr stars

3. THE AGES

Estimating GC ages using ΔV_{HB}^{TO} requires an accurate measurement of V(TO) and V(HB), along with an estimate of [Fe/H]. Continued advances in CCD technology and image reduction, along with the advent of the *Hubble Space Telescope*, have lead to a wealth of high-quality CMDs of GCs in recent years. Table 2 lists various observational quantities for 43 GCs for which reliable age determinations may be made based on published observations of V(TO) and V(HB). To be conservative, M22 and ω Cen have not been included in this group, as there is evidence for a range in metallicity in these clusters (Noble et al. 1991; Smith 1987) that complicates the age determination process. References for V(TO) and V(HB) are provided in the table. In some cases, the observers do not quote V(HB); rather, they provide the apparent magnitude of the zero-age horizontal branch [V(ZAHB)]. These have been converted to mean HB magnitudes using equation (4) from Carney et al. {1992: $V(\mathrm{HB}) = V(\mathrm{ZAHB}) - 0.05[\mathrm{Fe/H}] - 0.20$}. The V(HB) (and corresponding ΔV_{HB}^{TO} values) that have been corrected for this effect are indicated by an asterisk next to the V(HB)

TABLE 2

GLOBULAR CLUSTER PARAMETERS

CLUSTER												REFERENCES	
NGC	Name	l	b	$E(B-V)$	[Fe/H]	V(HB)[a]	ΔV_{HB}^{TO}[b]	R_{GC} (kpc)	R_{apo} (kpc)	HB TYPE	GROUP[c]	HB	TO
104	47 Tuc	305°896	−44°900	0.04	−0.71 ± 0.08	14.09	3.61 ± 0.10	7.3	7.3	−1.00 ± 0.03	D	1	1
288		151.328	−89.383	0.04	−1.40 ± 0.12	15.27*	3.73 ± 0.12	11.2	11.5	0.95 ± 0.08	OH	2	2
362		301.533	−46.248	0.06	−1.27 ± 0.07	15.29*	3.56 ± 0.14	8.8	9.2	−0.87 ± 0.08	YH	2	2
1261		270.541	−52.126	0.00	−1.31 ± 0.09	16.57*	3.57 ± 0.12	16.8	...	−0.70 ± 0.10	YH	3	3
1851		244.514	−35.037	0.02	−1.36 ± 0.09	16.15	3.45 ± 0.10	16.5	...	−0.33 ± 0.08	YH	4	4
1904	M79	227.229	−29.351	0.01	−1.69 ± 0.09	16.03*	3.57 ± ...	17.8	...	0.89 ± 0.16	OH	5	5
2298		245.628	−16.007	0.08	−1.85 ± 0.11	16.11	3.49 ± 0.21	16.1	...	0.93 ± 0.24	OH	6	6
2808		282.192	−11.253	0.22	−1.37 ± 0.09	15.97*	3.63 ± 0.14	10.2	...	−0.54 ± 0.06	YH	2	2
3201		277.228	8.641	0.21	−1.61 ± 0.12	14.76	3.39 ± 0.17	8.8	...	0.08 ± 0.06	YH	7	8
4147		252.850	77.189	0.02	−1.80 ± 0.14	17.00	3.60 ± ...	20.5	25.7	0.55 ± 0.14	YH	9	9
4590	M68	299.626	36.052	0.07	−2.09 ± 0.11	15.64	3.42 ± 0.10	9.6	...	0.44 ± 0.05	YH	10	10
5024	M53	332.965	79.765	0.00	−2.04 ± 0.08	16.90	3.55 ± 0.14	18.9	...	0.76 ± 0.10	OH	11	12
5053		335.695	78.944	0.06	−2.41 ± 0.06	16.65	3.48 ± ...	16.2	...	0.61 ± 0.18	OH	13	14
5272	M3	42.208	78.708	0.01	−1.66 ± 0.06	15.63	3.54 ± 0.09	11.7	18.3	0.08 ± 0.04	YH	15	15
5466		42.150	73.592	0.00	−2.22 ± 0.36	16.62	3.58 ± ...	16.7	29.2	0.68 ± 0.14	OH	16	17
5897		342.946	30.294	0.06	−1.68 ± 0.11	16.35	3.60 ± 0.18	7.6	...	0.91 ± 0.10	OH	18	18
5904	M5	3.863	46.796	0.03	−1.40 ± 0.06	14.98*	3.62 ± 0.11	6.0	21.1	0.37 ± 0.06	OH	2	2
6101		317.747	−15.825	0.04	−1.81 ± 0.15	16.60	3.40 ± ...	10.7	...	0.84 ± 0.16	OH	19	19
6121	M4	350.974	15.972	0.40	−1.33 ± 0.10	13.22*	3.68 ± 0.16	6.4	6.4	−0.07 ± 0.10	OH	2	2
6171	M107	3.374	23.011	0.31	−0.99 ± 0.06	15.55*	3.75 ± 0.18	3.6	3.9	−0.76 ± 0.08	OH	2	2
6205	M13	59.008	40.912	0.02	−1.65 ± 0.06	14.83*	3.67 ± 0.21	8.2	18.9	0.97 ± 0.08	OH	2	2
6218	M12	15.717	26.313	0.17	−1.34 ± 0.09	14.90	3.45 ± ...	4.3	4.5	0.92 ± 0.10	OH	20	21
6254	M10	15.138	23.077	0.32	−1.60 ± 0.08	14.65	3.75 ± 0.15	4.9	...	0.94 ± 0.10	OH	22	23
6341	M92	68.339	34.860	0.02	−2.24 ± 0.08	14.96*	3.74 ± 0.12	9.1	9.3	0.88 ± 0.08	OH	2	2
6352		341.421	−7.167	0.21	−0.51 ± 0.08	15.13	3.67 ± 0.10	3.6	...	−1.00 ± 0.04	D	24	24
6397		338.165	−11.958	0.18	−1.91 ± 0.14	12.90*	3.74 ± 0.14	6.1	6.1	0.93 ± 0.10	OH	2	2
6535		27.177	10.436	0.44	−1.75 ± 0.15	15.73	3.66 ± 0.19	4.2	...	1.00 ± ...	OH	25	25
6584		342.144	−16.414	0.07	−1.54 ± 0.15	16.53	3.47 ± ...	6.9	...	−0.09 ± 0.06	YH	26	26
6652		1.534	−11.377	0.10	−0.89 ± 0.15	15.85	3.35 ± 0.16	1.9	...	−1.00 ± ...	OH	27	27
6752		336.496	−25.627	0.04	−1.54 ± 0.09	13.63*	3.77 ± 0.16	5.4	...	1.00 ± 0.04	OH	2	2
6809	M55	8.795	−23.270	0.06	−1.82 ± 0.15	14.24*	3.66 ± 0.10	4.1	...	0.91 ± 0.10	OH	2	2
6838	M71	56.744	−4.564	0.27	−0.58 ± 0.08	14.44	3.56 ± 0.09	6.8	6.7	−1.00 ± 0.04	D	28	28
7006		63.770	−19.407	0.05	−1.59 ± 0.07	18.80	3.55 ± 0.12	36.8	...	−0.11 ± 0.06	YH	29	29
7078	M15	65.013	−27.313	0.10	−2.15 ± 0.08	15.77*	3.63 ± 0.16	9.9	10.2	0.72 ± 0.10	OH	2	2
7099	M30	27.180	−46.835	0.04	−2.1 ± 0.13	15.11*	3.62 ± 0.14	6.9	...	0.88 ± 0.12	OH	2	2
7492		53.386	−63.478	0.00	−1.82 ± 0.30	17.52*	3.72 ± 0.14	23.2	...	0.90 ± 0.18	OH	2	2
	Ter 7	3.387	−20.063	0.06	−0.36 ± 0.09	17.76	3.20 ± 0.12	14.3	...	−1.00 ± ...	YH	30	30
	Ter 8	5.758	−24.558	0.20	−1.99 ± 0.08	17.85	3.65 ± ...	14.3	...	1.00 ± ...	OH	31	32
	Rup 106	300.888	11.670	0.20	−1.69 ± 0.05	17.73*	3.32 ± 0.07	17.0	...	−0.82 ± 0.15	YH	33	33
	Pal 5	0.852	45.860	0.03	−1.47 ± 0.29	17.27*	3.53 ± 0.14	15.4	16.9	−0.40 ± 0.20	YH	2	2
	Pal 12	30.510	−47.680	0.02	−1.14 ± 0.20	17.13	3.30 ± ...	15.1	...	−1.00 ± 0.12	YH	34	34
	IC 4499	307.354	−20.473	0.25	−1.75 ± 0.20	17.80	3.25 ± 0.15	15.7	...	0.11 ± 0.36	YH	35	35
	Arp 2	8.543	−20.787	0.08	−1.70 ± 0.11	18.18*	3.29 ± 0.10	21.5	...	0.86 ± ...	OH	36	36

[a] Entries with an asterisk (*) were originally published as V(ZAHB). The V(HB) and ΔV_{HB}^{TO} values have been corrected using $V(\mathrm{HB}) = V_{ZAHB} - 0.05[\mathrm{Fe/H}] - 0.20$ (eq. [4] from Carney et al. 1992).

[b] Errors given in ΔV_{HB}^{TO} are those quoted in the original papers and are not 1 σ Gaussian errors. As discussed in the Appendix, a reasonable estimate of the 1 σ Gaussian error may be obtained by multipling the quoted errors by 0.61.

[c] D ≡ disk; OH ≡ old halo; YH ≡ younger halo.

REFERENCES.—(1) Hesser et al. 1987; (2) Buonanno, Corsi, & Fusi Pecci 1989; (3) Ferraro et al. 1993; (4) Walker 1992b; (5) Ferraro et al. 1992a; (6) Janes & Heasley 1988; (7) Alcaino, Liller, & Alvarado 1989; (8) Brewer et al. 1993; (9) Friel, Heasley, & Christian 1987; (10) Walker 1994; (11) Cuffey 1965; (12) Heasley & Christian 1991; (13) Sarajedini & Milone 1995; (14) Fahlman, Richer, & Nemec 1991; (15) Buonanno et al. 1994a; (16) Nemec & Harris 1987; (17) Peterson 1986; (18) Sarajedini 1992; (19) Sarajedini & Da Costa 1991; (20) Racine 1971; (21) Sato, Richer, & Fahlman 1989; (22) Hurley, Richer, & Fahlman 1989; (23) Harris, Racine, & deRoux 1976; (24) Fullton et al. 1995; (25) Sarajedini 1994; (26) Sarajedini & Forrester 1995; (27) Ortolani, Bica, & Barbuy 1994; (28) Hodder et al. 1992; (29) Buonanno et al. 1991; (30) Buonanno et al. 1995b; (31) Da Costa & Armandroff 1995; (32) Ortolani & Gratton 1990; (33) Buonanno et al. 1993; (34) Stetson et al. 1989; (35) Ferraro et al. (1995); (36) Buonanno et al. 1995a.

value in Table 2. Our 1992 compilation (Chaboyer et al. 1992) does NOT include a correction for this effect, as we were not aware that some observers quoted V(ZAHB).

The cluster [Fe/H] values and their errors are taken from Zinn & West (1984), except for NGC 4147 and NGC 5053 (Armandroff, Da Costa, & Zinn 1992); NGC 6218, Ter 7, Ter 8, and Arp 2 (Da Costa & Armandroff 1995); and Rup 106 (Da Costa, Armandroff, & Norris 1992). The reddennings are from Zinn (1985), except for NGC 4590 (Walker 1994), NGC 5053 (Sarajedini & Milone 1995), NGC 6352 (Fullton et al. 1995), NGC 6535 (Sarajedini 1994), NGC 6584 (Sarajedini & Forrester 1995), NGC 6652 (Ortolani, Bica, & Barbuy 1994), Ter 7 (Webbink 1985), Ter 8 (Ortolani & Gratton 1990), Arp 2 (Buonanno et al. 1995a), and Rup 106 (Da Costa et al. 1992). The Galactic coordinates for the clusters are taken from Shawl & White (1986), except for Rup 106 and Pal 12, which are from Webbink (1985). The HB types are from Lee et al. (1994), with the exceptions of NGC 4590 (Walker 1994), NGC 6584 (Sarajedini & Forrester 1995), NGC 6535 (Sarajedini 1994), NGC 6652 (Ortolani et al. 1994), Ter 7 and Arp 2 (Buonanno et al. 1995a, b), Ter 8 (Ortolani & Gratton 1990), and IC 4499 (Ferraro et al. 1995). The groupings into disk, old halo, and younger halo clusters are from Zinn & Lee (1996; see also Zinn 1993). In calculating the Galactocentric distance (R_{GC}) of each cluster, we have adopted $R_{\odot} = 8.0$ kpc, $A_V = 3.2E(B-V)$, and a distance modulus derived from V(HB) and our preferred M_v(RR) relation $\{M_v(\mathrm{RR}) = 0.20[\mathrm{Fe/H}] + 0.98\}$. Proper-motion studies exist for 16 of the GCs in our sample, and these have been used by Majewski (1994) to determine the apogalactica distances (R_{apo}) listed in Table 2. As expected, most of the apogalactica distances are quite similar to the Galactocentric distances. However, there are a few notable exceptions. The present positions of NGC 5466, NGC 5904, and NGC 6205 are considerably smaller than their apogalactica distances.

Using the ΔV_{HB}^{TO} and [Fe/H] values listed in Table 2, GC ages are derived using equation (2), with the β coefficients listed in Table 1. The error in the derived age is calculated by propagating the errors in ΔV_{HB}^{TO} and [Fe/H] through equation (2). The error in the derived age is dominated by the error in ΔV_{HB}^{TO}. For the statistical analysis that comprises the bulk of this paper, it is important that the error in ΔV_{HB}^{TO} represent a Gaussian 1 σ error bar. However, it is doubtful that the observers quote such an error bar. In order to get an estimate for the Gaussian 1 σ error bar, the literature has been searched for independent measurements of ΔV_{HB}^{TO}. The Appendix presents an analysis of these independent observations and concludes that a reliable estimate for the Gaussian 1 σ error in ΔV_{HB}^{TO} may be obtained by multiplying the quoted error by 0.61. We have applied this correction factor to all of the quoted ΔV_{HB}^{TO} errors when determining the error in the derived age. In some cases, errors in ΔV_{HB}^{TO} were not given by the observers. For these clusters, an error of 0.083 mag was assumed. This is the average of the Gaussian 1 σ errors for those clusters with quoted errors in ΔV_{HB}^{TO}.

Table 3 presents ages for the 43 GCs, using the 10 different M_v(RR) relations given in Table 1. The heading of each column gives the M_v(RR) relation used to derive the ages in that column. These ages will be analyzed in detail in the following sections. Here, we simply note that ages derived using the Layden et al. (1994) zero point for M_v(RR) are approximately 25% larger than the ages derived using the Walker zero point (e.g., compare the sixth and seventh columns). This illustrates the well-known result that a 0.25 mag uncertainty in the distance modulus translates into a 25% uncertainty in ages derived using ΔV_{HB}^{TO}. It is also interesting to note that there are several young clusters in the sample; IC 4499, Arp 2, Pal 12, Rup 106, and Ter 7 have all been shown to be young by the $\Delta(B-V)$ technique (see Buonanno et al. 1994b), and indeed, the ΔV_{HB}^{TO} ages for these clusters are all young compared to the mean age. NGC 6652, which has a small ΔV_{HB}^{TO} value (Ortolani et al. 1994), also appears to be young.

Among these young clusters, Ter 7 stands out with an age of ~9 Gyr, which is at least 2 Gyr younger than the others. It appears that Ter 7 is associated with the recently discovered Sgr dwarf spheroidal galaxy (Ibata, Gilmore, & Irwin 1994). Indeed Ter 7, Ter 8, Arp 2, and M54 (not on our list) are located at *approximately* the same distance and the same region of the sky as Sgr. In addition, Da Costa & Armandroff (1995) have shown that the above clusters have similar radial velocities to that of Sgr. However, an inspection of Table 2 reveals that Ter 7 and Ter 8 have $R_{GC} = 14.3$ kpc, while Arp 2 has $R_{GC} = 21.5$ kpc. Using the reddening, metallicity, and V(HB) listed by Da Costa & Armandroff (1995) along with our preferred M_v(RR) relation, the Sgr dwarf is located at $R_{GC} = 15.6$ kpc. This rather large range in R_{GC} suggests that perhaps Ter 7, Ter 8, and Arp 2 are not associated with Sgr. However, there are considerable uncertainties associated with determining the Galactocentric distances; errors in the reddening, metallicity, the magnitude of the HB, and the uncertainty in the correct M_v(RR) relation all lead to uncertainty in the derived R_{GC} distances. In this regard, we note that slightly different choices for the input parameters can yield Galactocentric distances that agree within 0.9 kpc for Ter 7, Ter 8, and Sgr, with Arp 2 still being somewhat anomalous, with a R_{GC} value that is about 3 kpc higher than the other objects. While a definitive answer will come only from proper-motion studies, it appears that Ter 7, Ter 8, and Sgr are associated. Although the evidence for Arp 2 being associated with Sgr is not as strong, it still remains a possibility, which should be investigated further. Thus, two of the anomalously young GCs were likely formed as part of Sgr and are now being accreted onto our Galaxy.

Lin & Richer (1992) and Buonanno et al. (1994b) have suggested that Pal 12, Arp 2, Rup 106, and Ter 7 may all have been captured by our Galaxy and represent later infall events. As such, they are not indicative of the early formation of the Galactic halo. This argument is based on the fact that these four clusters lie along a single great circle, which passes through the Magellanic Stream. A similar argument holds for IC 4499 (Fusi Pecci, Bellazzini, & Ferraro 1995). However, even if they have been captured by the Galaxy, their formation occurred within the halo. It is clear that these young clusters formed much later than the majority of GCs in the Galactic halo. Thus, it is true that these clusters were not part of the early halo formation in the Galaxy. However, whether these clusters are later accretion events or not, they are part of the Galactic halo and so give us insights into its formation.

4. AGE, METALLICITY, AND GALACTOCENTRIC DISTANCE

The question of whether or not an age-metallicity relationship exists in the Galactic halo is a long-standing

TABLE 3

GLOBULAR CLUSTER AGES

Name (1)	0.17 [Fe/H] +0.79 Age (2)	0.20 [Fe/H] +0.98 Age (3)	0.15 [Fe/H] +0.98 Age (4)	0.15 [Fe/H] +0.725 Age (5)	0.20 [Fe/H] +1.06 Age (6)	0.20 [Fe/H] +0.82 Age (7)	0.25 [Fe/H] +1.14 Age (8)	0.25 [Fe/H] +0.915 Age (9)	0.30 [Fe/H] +1.22 Age (10)	0.30 [Fe/H] +1.01 Age (11)
104	12.4 ± 1.1	15.6 ± 1.3	16.4 ± 1.3	11.6 ± 1.0	17.3 ± 1.4	12.6 ± 1.1	18.4 ± 1.5	13.6 ± 1.2	19.4 ± 1.5	14.8 ± 1.2
288	16.5 ± 1.3	19.4 ± 1.6	20.9 ± 1.7	15.8 ± 1.3	21.1 ± 1.7	16.2 ± 1.3	21.4 ± 1.7	16.7 ± 1.3	21.7 ± 1.7	17.3 ± 1.4
362	14.3 ± 1.7	17.4 ± 2.0	18.9 ± 2.1	13.5 ± 1.6	19.3 ± 2.1	14.1 ± 1.7	19.8 ± 2.2	14.7 ± 1.7	20.3 ± 2.2	15.3 ± 1.8
1261	13.7 ± 1.1	16.2 ± 1.3	17.4 ± 1.4	13.1 ± 1.1	17.6 ± 1.4	13.5 ± 1.1	17.9 ± 1.4	14.0 ± 1.1	18.3 ± 1.5	14.5 ± 1.2
1851	12.0 ± 0.8	14.2 ± 1.0	15.3 ± 1.1	11.6 ± 0.8	15.5 ± 1.1	11.9 ± 0.8	15.7 ± 1.1	12.3 ± 0.8	16.0 ± 1.1	12.7 ± 0.8
1904	14.5 ± 1.3	16.9 ± 1.5	18.5 ± 1.7	14.1 ± 1.3	18.4 ± 1.7	14.2 ± 1.3	18.3 ± 1.7	14.4 ± 1.3	18.4 ± 1.6	14.7 ± 1.3
2298	13.9 ± 1.9	16.0 ± 2.2	17.7 ± 2.5	13.4 ± 1.8	17.4 ± 2.4	13.5 ± 1.8	17.2 ± 2.4	13.5 ± 1.8	17.1 ± 2.3	13.7 ± 1.9
2808	14.7 ± 1.4	17.3 ± 1.6	18.7 ± 1.8	14.1 ± 1.3	18.9 ± 1.8	14.5 ± 1.4	19.2 ± 1.8	15.0 ± 1.4	19.5 ± 1.8	15.5 ± 1.4
3201	11.9 ± 1.3	13.8 ± 1.6	15.0 ± 1.7	11.5 ± 1.3	15.1 ± 1.7	11.6 ± 1.3	15.0 ± 1.7	11.8 ± 1.3	15.1 ± 1.7	12.1 ± 1.3
4147	15.4 ± 1.4	17.9 ± 1.6	19.7 ± 1.8	14.9 ± 1.4	19.5 ± 1.8	15.0 ± 1.4	19.3 ± 1.7	15.1 ± 1.4	19.1 ± 1.7	15.3 ± 1.4
4590	13.6 ± 0.9	15.5 ± 1.0	17.3 ± 1.2	13.2 ± 0.9	16.8 ± 1.1	13.1 ± 0.9	16.4 ± 1.1	13.0 ± 0.8	16.0 ± 1.0	12.9 ± 0.8
5024	15.4 ± 1.4	17.6 ± 1.6	19.6 ± 1.8	15.0 ± 1.4	19.2 ± 1.7	14.9 ± 1.3	18.7 ± 1.7	14.8 ± 1.3	18.4 ± 1.7	14.8 ± 1.3
5053	15.5 ± 1.3	17.4 ± 1.5	19.7 ± 1.7	15.2 ± 1.3	18.9 ± 1.6	14.9 ± 1.2	18.2 ± 1.6	14.5 ± 1.2	17.4 ± 1.5	14.1 ± 1.2
5272	14.1 ± 0.8	16.4 ± 1.0	17.9 ± 1.1	13.6 ± 0.8	17.9 ± 1.1	13.8 ± 0.8	17.8 ± 1.1	14.0 ± 0.8	17.8 ± 1.1	14.2 ± 0.8
5466	16.5 ± 1.9	18.7 ± 2.0	21.0 ± 2.4	16.1 ± 1.9	20.3 ± 2.1	15.9 ± 1.7	19.7 ± 1.9	15.6 ± 1.5	19.1 ± 1.7	15.4 ± 1.4
5897	15.1 ± 1.8	17.5 ± 2.1	19.2 ± 2.3	14.6 ± 1.8	19.1 ± 2.3	14.7 ± 1.8	19.0 ± 2.3	14.9 ± 1.8	19.0 ± 2.3	15.2 ± 1.8
5904	14.6 ± 1.1	17.2 ± 1.3	18.6 ± 1.4	14.0 ± 1.0	18.8 ± 1.4	14.4 ± 1.1	19.0 ± 1.4	14.8 ± 1.1	19.2 ± 1.4	15.3 ± 1.1
6101	12.5 ± 1.2	14.4 ± 1.3	15.9 ± 1.5	12.1 ± 1.1	15.7 ± 1.5	12.2 ± 1.1	15.5 ± 1.4	12.3 ± 1.1	15.4 ± 1.4	12.4 ± 1.1
6121	15.5 ± 1.7	18.3 ± 2.0	19.6 ± 2.1	14.8 ± 1.6	19.9 ± 2.1	15.3 ± 1.6	20.2 ± 2.1	15.8 ± 1.7	20.6 ± 2.2	16.4 ± 1.7
6171	15.7 ± 1.9	18.8 ± 2.3	19.9 ± 2.4	15.0 ± 1.8	20.5 ± 2.5	15.7 ± 1.9	21.2 ± 2.5	16.6 ± 2.0	21.9 ± 2.6	17.4 ± 2.1
6205	16.1 ± 2.2	18.8 ± 2.6	20.5 ± 2.8	15.5 ± 2.1	20.5 ± 2.8	15.8 ± 2.2	20.4 ± 2.8	16.0 ± 2.2	20.4 ± 2.8	16.3 ± 2.2
6218	12.0 ± 1.1	14.1 ± 1.3	15.2 ± 1.4	11.5 ± 1.0	15.4 ± 1.4	11.9 ± 1.1	15.6 ± 1.4	12.2 ± 1.1	15.9 ± 1.5	12.7 ± 1.1
6254	17.4 ± 1.7	20.4 ± 2.0	22.2 ± 2.2	16.8 ± 1.7	22.2 ± 2.1	17.1 ± 1.7	22.2 ± 2.1	17.4 ± 1.7	22.3 ± 2.1	17.8 ± 1.7
6341	19.4 ± 1.5	22.1 ± 1.7	24.8 ± 1.9	19.0 ± 1.4	24.0 ± 1.8	18.7 ± 1.4	23.3 ± 1.7	18.4 ± 1.4	22.6 ± 1.7	18.2 ± 1.4
6352	12.9 ± 1.1	16.3 ± 1.3	16.8 ± 1.3	12.0 ± 1.0	17.9 ± 1.4	13.2 ± 1.1	19.3 ± 1.5	14.5 ± 1.2	20.6 ± 1.5	15.9 ± 1.3
6397	18.4 ± 1.7	21.2 ± 1.9	23.4 ± 2.2	17.8 ± 1.7	23.0 ± 2.1	17.8 ± 1.6	22.7 ± 2.0	17.8 ± 1.6	22.4 ± 2.0	18.0 ± 1.6
6535	16.3 ± 2.1	18.9 ± 2.4	20.8 ± 2.6	15.8 ± 2.0	20.6 ± 2.6	15.9 ± 2.0	20.4 ± 2.5	16.0 ± 2.0	20.4 ± 2.5	16.3 ± 2.0
6584	12.7 ± 1.2	14.9 ± 1.4	16.2 ± 1.6	12.3 ± 1.2	16.2 ± 1.5	12.5 ± 1.2	16.3 ± 1.5	12.8 ± 1.2	16.4 ± 1.5	13.1 ± 1.2
6652	9.1 ± 1.3	11.4 ± 1.7	12.2 ± 1.8	8.5 ± 1.2	12.8 ± 1.8	9.1 ± 1.3	13.5 ± 1.9	9.8 ± 1.4	14.1 ± 1.9	10.5 ± 1.5
6752	17.7 ± 1.9	20.7 ± 2.2	22.5 ± 2.3	17.0 ± 1.8	22.5 ± 2.3	17.4 ± 1.8	22.6 ± 2.3	17.7 ± 1.8	22.8 ± 2.3	18.2 ± 1.9
6809	16.5 ± 1.2	19.1 ± 1.3	21.0 ± 1.5	16.0 ± 1.2	20.8 ± 1.4	16.1 ± 1.1	20.5 ± 1.4	16.1 ± 1.1	20.4 ± 1.3	16.3 ± 1.1
6838	11.3 ± 0.9	14.3 ± 1.1	14.8 ± 1.1	10.5 ± 0.8	15.8 ± 1.1	11.5 ± 0.9	16.9 ± 1.2	12.5 ± 0.9	18.0 ± 1.3	13.7 ± 1.0
7006	14.0 ± 1.1	16.4 ± 1.3	17.9 ± 1.4	13.5 ± 1.1	17.9 ± 1.4	13.8 ± 1.1	17.9 ± 1.4	14.0 ± 1.1	18.0 ± 1.4	14.3 ± 1.1
7078	17.1 ± 1.7	19.5 ± 2.0	21.9 ± 2.2	16.7 ± 1.7	21.2 ± 2.2	16.5 ± 1.7	20.7 ± 2.1	16.3 ± 1.7	20.2 ± 2.1	16.2 ± 1.7
7099	16.9 ± 1.6	19.3 ± 1.8	21.6 ± 2.0	16.5 ± 1.5	21.0 ± 1.9	16.3 ± 1.5	20.4 ± 1.8	16.1 ± 1.5	19.9 ± 1.8	16.0 ± 1.4
7492	17.6 ± 1.9	20.3 ± 2.0	22.4 ± 2.4	17.0 ± 1.9	22.1 ± 2.2	17.1 ± 1.7	21.9 ± 2.1	17.2 ± 1.6	21.7 ± 2.0	17.4 ± 1.6
Ter 7	7.2 ± 0.5	8.7 ± 0.8	9.0 ± 0.8	6.8 ± 0.4	9.7 ± 0.9	7.3 ± 0.5	10.6 ± 1.0	7.9 ± 0.7	11.4 ± 1.1	8.7 ± 0.8
Ter 8	16.9 ± 1.5	19.4 ± 1.7	21.5 ± 1.9	16.4 ± 1.5	21.1 ± 1.8	16.4 ± 1.4	20.7 ± 1.8	16.3 ± 1.4	20.4 ± 1.8	16.3 ± 1.4
Rup 106......	13.2 ± 0.8	15.7 ± 0.9	17.4 ± 1.0	12.7 ± 0.8	17.4 ± 1.0	12.9 ± 0.8	17.3 ± 1.0	13.0 ± 0.8	17.2 ± 1.0	13.2 ± 0.8
Pal 5	13.4 ± 1.4	15.7 ± 1.6	17.0 ± 1.9	12.9 ± 1.4	17.1 ± 1.8	13.2 ± 1.4	17.2 ± 1.7	13.5 ± 1.3	17.4 ± 1.6	13.9 ± 1.3
Pal 12	9.4 ± 1.4	11.7 ± 1.7	12.6 ± 1.9	8.8 ± 1.4	13.1 ± 1.8	9.3 ± 1.4	13.5 ± 1.8	9.8 ± 1.4	13.9 ± 1.8	10.4 ± 1.4
IC 4499	10.6 ± 1.1	12.2 ± 1.2	13.4 ± 1.4	10.3 ± 1.0	13.3 ± 1.3	10.4 ± 1.0	13.1 ± 1.3	10.4 ± 1.0	13.1 ± 1.3	10.6 ± 1.0
Arp 2.........	12.3 ± 0.8	14.2 ± 1.0	15.6 ± 1.1	11.9 ± 0.8	15.5 ± 1.1	12.0 ± 0.8	15.4 ± 1.0	12.1 ± 0.8	15.4 ± 1.0	12.4 ± 0.8

problem. It has long been realized that if M_v(RR) has a shallow slope with metallicity, then an age-metallicity relationship will exist, with the most metal-poor clusters being the oldest (e.g., Sandage 1982; Sarajedini & King 1989). This trend is illustrated in Figure 1, which plots the age as a function of metallicity, assuming $M_v(\mathrm{RR}) = 0.20[\mathrm{Fe/H}] + 0.98$. A least-squares fit to all of the data, which takes into account the error bars in both coordinates (Press et al. 1992), yields $t_9 = (-4.0 \pm 0.4)[\mathrm{Fe/H}] + (9.8 \pm 0.7)$, with the probability of a nonzero slope being greater than 99.999%. If the disk clusters (47 Tuc, NGC 6352, and NGC 6838) and the GCs that are likely associated with Sgr (Ter 7, Ter 8, and Arp 2) are removed from the fit (to leave a pure halo sample), then the least-squares solution yields $t_9 = (-4.4 \pm 0.9)[\mathrm{Fe/H}] + (9.3 \pm 1.4)$, with the probability of a nonzero slope being greater than 99.999%. If the sample is further divided by removing the remaining young clusters or metal-rich clusters ($[\mathrm{Fe/H}] > -1$; NGC 6171, NGC 6652, Rup 106, IC 4499, and Pal 12), then we find $t_9 = (-3.4 \pm 1.0)[\mathrm{Fe/H}] + (11 \pm 2)$, with the probability of an age-metallicity relation existing being greater than 99.7%. Note that the above results are contingent upon a constant [α/Fe] below $[\mathrm{Fe/H}] = -1.0$, as this was assumed in the isochrones. However, we note that to remove the age-metallicity trend observed would require that [α/Fe] increase by 0.8 dex, from $[\mathrm{Fe/H}] = -2.2$ to $[\mathrm{Fe/H}] = -1.2$, the [Fe/H] range spanned by the majority of the GCs in the sample. However, such a dramatic change in [α/Fe] is not consistent with the halo star observations, as discussed in § 2.1.

To explore the age-metallicity question further, GC ages have been determined using our best estimate for the M_v(RR) zero point and slopes ranging from 0.15 to 0.30, in steps of 0.002. The resulting ages were then analyzed using the least-squares fit as above, in order to examine how the slope of M_v(RR) with metallicity affects the age-metallicity relationship. The results are shown in Figure 2, which plots the probability of an age-metallicity relation as a function of the M_v(RR) slope with metallicity. If all clusters are included in the analysis, then an age-metallicity relation exists at the greater than 99.9% confidence level for all values of the slope tested (from 0.15 to 0.30). If the disk clusters and the GCs associated with Sgr are removed from the fit, leaving a pure halo sample, then an age-metallicity relationship exists at a greater than 97.6% confidence level for all slopes less than or equal to 0.3. If the young and/or metal-rich clusters are excluded, then an age-metallicity relationship exists at the 2σ (95%) level, provided that the slope of M_v(RR) with metallicity is less than 0.259. As most evidence favors low values for the M_v(RR) slope (see also § 6), Figure 2 demonstrates that an age-metallicity relationship exists in the halo of our Galaxy.

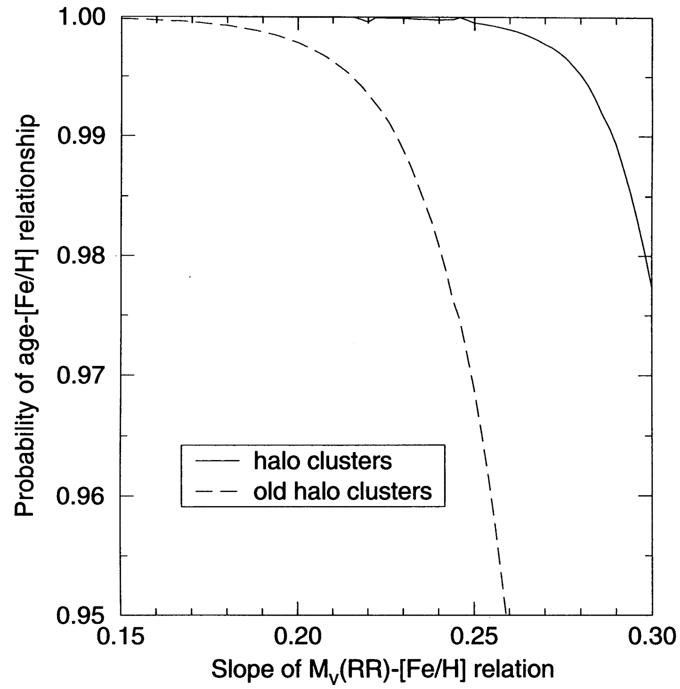

FIG. 2.—The probability of an age-metallicity relation is plotted as a function of the slope with metallicity of M_v(RR). If all clusters are included (not plotted), then the probability is greater than 0.999 for all values of the slope. The halo cluster sample does not include 47 Tuc, NGC 6352, NGC 6838, Ter 7, Ter 8, and Arp 2, while the old halo sample excludes NGC 6171, 6652, Rup 106, IC 4499, and Pal 12 in addition to the above clusters. Provided that the slope of M_v(RR) with metallicity is less than 0.26, an age-metallicity relationship exists in the halo, regardless of which sample is used to define the halo.

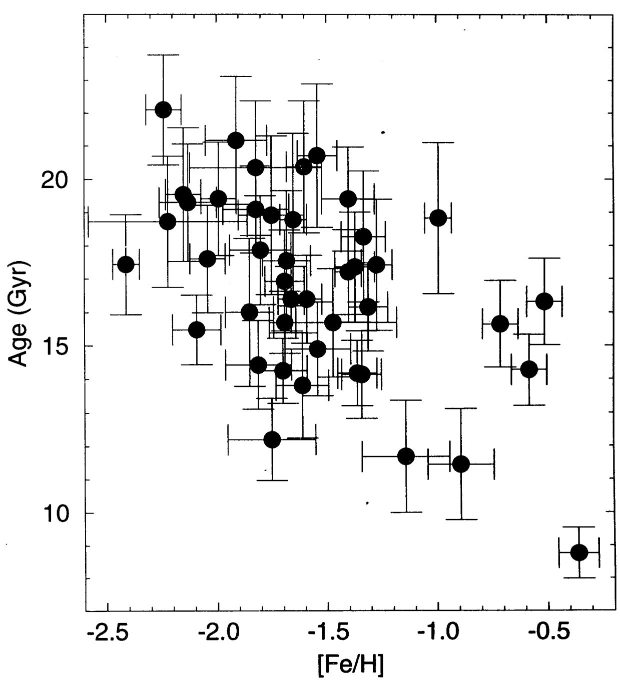

FIG. 1.—Age as a function of metallicity for 43 GCs, assuming $M_v(\mathrm{RR}) = 0.20[\mathrm{Fe/H}] + 0.98$.

The relationship between age and Galactocentric distance is shown in Figure 3, which plots age {assuming $M_v(\mathrm{RR}) = 0.20[\mathrm{Fe/H}] + 0.98$} as a function of R_{GC}. The sample has been classified into old halo, younger halo, and disk clusters based on metallicity, kinematics, and HB morphology (Zinn 1993). This will be discussed in more detail in § 5. Here we note that no clear relationship between age and Galactocentric distance exists, though there is a suggestion that GCs become younger as one goes to large Galactocentric distances. A least-squares fit to the data yields $t_9 = (-0.06 \pm 0.03)R_{\mathrm{GC}} + (16.5 \pm 0.7)$ with nonzero slope being significant only at the 94.5% confidence level. If the apogalactica distances given in Table 2 are substituted for R_{GC} where available, then the significance of the nonzero slope drops below 50%. Using ages and distances derived from the other HB relationships given in Table 1 results in similar plots. Hence, the present data provide no com-

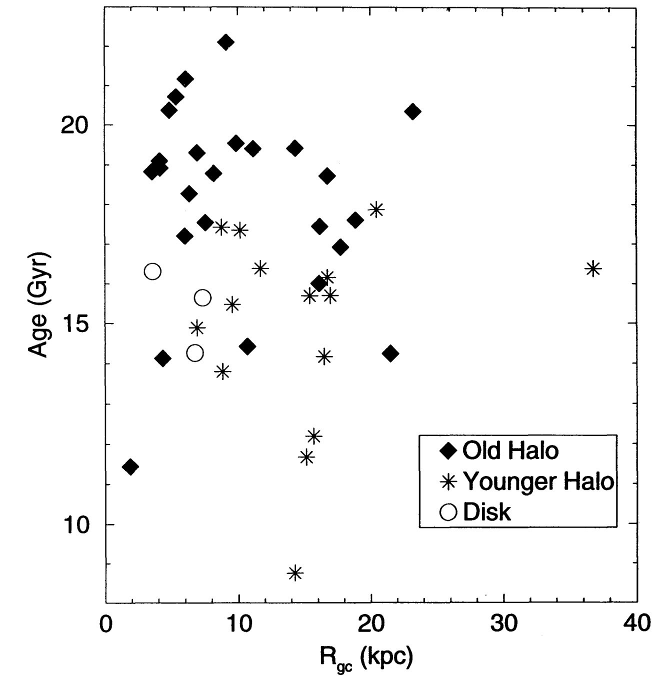

FIG. 3.—Age as a function of Galactocentric distance (R_{GC}) for 43 GCs, assuming M_v(RR) = 0.20[Fe/H] + 0.98. The sample has been classified into old halo, younger halo, and disk clusters based on metallicity, kinematics, and HB morphology (Zinn 1993). Error bars have not been plotted for clarity but are typically ± 1.6 Gyr.

pelling evidence for an age–Galactocentric distance relationship.

5. AGE RANGE

In Table 3 there is a wide range of GC ages for a given M_v(RR) relation. Clearly, some of this is due to the relatively large errors (of order ± 1.6 Gyr) in the individual age determinations. To quantify how much of the age range is due to the errors and whether an intrinsic age range exists within the GC system, the following statistical test was performed: an "expected" distribution for no intrinsic age range was constructed by randomly generating 10,000 ages using a Gaussian distribution, with a mean given by the mean age of the entire sample, and the sigma (i.e., standard deviation) given by the error in an individual age determination. This is repeated for all clusters in the sample, so that the expected distribution contains 43 × 10,000 = 430,000 ages. This expected distribution is then compared to the actual age distribution, using the F-test (Press et al. 1992), which determines if the two distributions have the same variance. If there is less than a 5% chance that the two distributions have the same variance, then we conclude that an age range exists. The size of the age range is inferred by the standard method, $\sigma_{\rm range} = (\sigma^2_{\rm obs} - \sigma^2_{\rm expected})^{1/2}$, where $\sigma_{\rm range}$ is the sigma of the true age range, $\sigma_{\rm obs}$ is the sigma of the actual data, and $\sigma_{\rm expected}$ is the sigma of our expected distribution, given the input errors in our ages. Tests have been performed that indicated that the typical error in our inferred $\sigma_{\rm range}$ is ± 0.1 Gyr for a given M_v(RR) relation.

When this analysis is performed on all 43 clusters, the F-test rejects the hypothesis of no intrinsic age range, at a very high confidence level for all M_v(RR) relations used in this paper. Figure 4 plots the actual age histogram for our preferred M_v(RR) relation, along with the expected histogram if there was no age range, and the best-fitting histogram, which includes an intrinsic range of ages, with $\sigma_{\rm range} = 2.3$ Gyr. If the age spread is defined to be the age range that includes 95% of the clusters, then the age spread inferred is 4 × 2.3 = 9.2 Gyr. The complete results of this analysis are presented in detail in Table 4 for all of the M_v(RR) relations.

When one looks at Figure 4, it is clear that the four very young clusters (Ter 7, Pal 12, IC 4499, and NGC 6652) are somewhat anomalous and are responsible for a good part of the very large inferred age range. Thus, the above analysis was repeated excluding the four very young clusters. This gives a reasonable estimate of the true age range among the bulk of the Galactic GCs. Even with this restricted sample, an intrinsic age range exists at the greater than 95% confidence level for all M_v(RR) relations (Table 4). The size of the age range is reduced and varies between 4.1 and 7.1 Gyr, depending on the choice of M_v(RR). The sensitivity of these results to the slope of the M_v(RR) relation with metallicity may be reduced by considering only those GCs in the restricted range $-1.8 <$ [Fe/H] < -1.3. There are 21 GCs in this group (the young clusters Ter 7, Pal 12, and NGC 6652 are not included), and the results are quite similar to those obtained with the sample that excludes the very young clusters. As shown in Table 4, an intrinsic age range exists regardless of the choice of M_v(RR). The age spread is 5.1–7.2, depending on the choice of M_v(RR). Thus, we may conclude that a real age spread of ∼5 Gyr exists among the bulk of the GCs, with several clusters (∼10%) that are considerably younger.

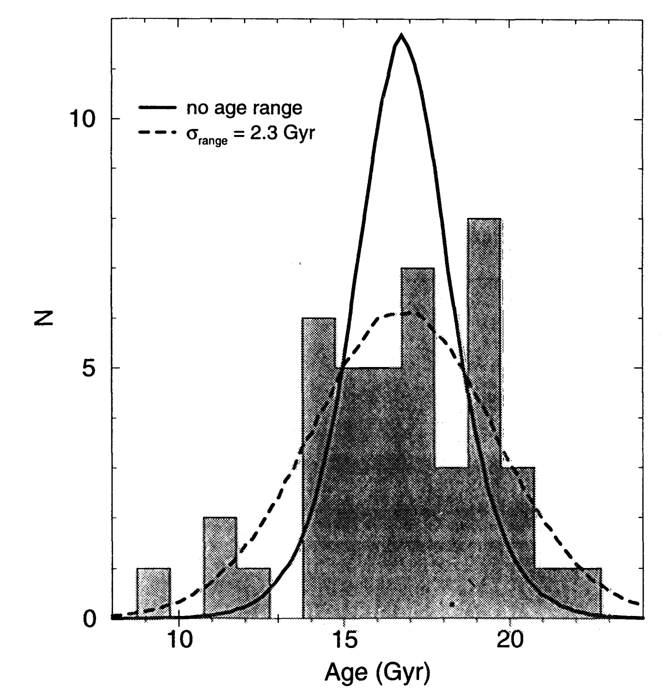

FIG. 4.—Histogram of ages for our preferred M_v(RR) relation. The solid line is the expected histogram of ages given the errors in the individual ages and assuming no intrinsic age range. It has been normalized to the total number of clusters in our sample (43). It is clearly not a good fit to the data, and the F-test rejects the hypothesis that the two distributions have the same variance at a very high confidence level. The dotted line shows the best-fitting Gaussian distribution, which includes an intrinsic age range of $\sigma_{\rm range} = 2.3$ Gyr, in addition to the scatter induced by the error in the individual ages.

TABLE 4

AGE RANGE

M_v(RR Lyr)	Probability of NO Age Range	σ_{range} (Gyr)	Age Spread
All Clusters ($N = 43$)			
0.17[Fe/H] + 0.79......	2.1×10^{-12}	2.2	8.7
0.20[Fe/H] + 0.98......	1.7×10^{-9}	2.3	9.2
0.15[Fe/H] + 0.98......	1.8×10^{-11}	2.7	10.8
0.15[Fe/H] + 0.72......	6.9×10^{-14}	2.2	8.9
0.20[Fe/H] + 1.06......	2.6×10^{-9}	2.4	9.8
0.20[Fe/H] + 0.82......	4.2×10^{-11}	2.0	8.1
0.25[Fe/H] + 1.14......	2.2×10^{-7}	2.2	8.8
0.25[Fe/H] + 0.91......	5.5×10^{-9}	1.9	7.5
0.30[Fe/H] + 1.22......	2.3×10^{-6}	2.1	8.3
0.30[Fe/H] + 1.01......	2.8×10^{-7}	1.8	7.0
Excluding Young Clusters ($N = 39$)			
0.17[Fe/H] + 0.79......	7.1×10^{-4}	1.4	5.7
0.20[Fe/H] + 0.98......	9.0×10^{-3}	1.4	5.6
0.15[Fe/H] + 0.98......	1.2×10^{-3}	1.8	7.1
0.15[Fe/H] + 0.72......	1.2×10^{-4}	1.5	6.0
0.20[Fe/H] + 1.06......	1.4×10^{-2}	1.5	5.9
0.20[Fe/H] + 0.82......	3.3×10^{-3}	1.3	5.1
0.25[Fe/H] + 1.14......	4.1×10^{-2}	1.3	5.2
0.25[Fe/H] + 0.91......	2.0×10^{-2}	1.1	4.4
0.30[Fe/H] + 1.22......	4.7×10^{-2}	1.3	5.1
0.30[Fe/H] + 1.01......	4.3×10^{-2}	1.0	4.1
Clusters with $-1.8 <$ [Fe/H] < -1.3 ($N = 21$)			
0.17[Fe/H] + 0.79......	1.9×10^{-2}	1.3	5.3
0.20[Fe/H] + 0.98......	1.0×10^{-2}	1.6	6.4
0.15[Fe/H] + 0.98......	1.9×10^{-2}	1.7	6.8
0.15[Fe/H] + 0.72......	1.6×10^{-2}	1.3	5.1
0.20[Fe/H] + 1.06......	1.3×10^{-2}	1.7	6.9
0.20[Fe/H] + 0.82......	1.9×10^{-2}	1.3	5.2
0.25[Fe/H] + 1.14......	1.0×10^{-2}	1.8	7.0
0.25[Fe/H] + 0.91......	1.3×10^{-2}	1.4	5.4
0.30[Fe/H] + 1.22......	7.7×10^{-3}	1.8	7.2
0.30[Fe/H] + 1.01......	6.0×10^{-3}	1.4	5.8

6. THE SECOND PARAMETER PROBLEM

The morphology of the HB (i.e., the relative number of red, blue, and RR Lyr stars on the HB) is primarily governed by the metallicity of the cluster. As such, [Fe/H] is the first parameter that controls HB morphology. However, it has long been known that two clusters with similar [Fe/H] values can have considerably different HB morphologies. NGC 288, NGC 362, M13, and M3 are classic examples of GCs that demonstrate that some other parameter besides [Fe/H] is important in determining the morphology of the HB. Searle & Zinn (1978) demonstrated that the second parameter is correlated with Galactocentric distance; there is a tight relationship between [Fe/H] and HB type in the inner halo ($R_{GC} < 8$ kpc), while the effects of the second parameter are most pronounced in the outer halo. The quest to determine the nature of the second parameter that governs HB morphology has been a long-standing one in astronomy. There are numerous possibilities for the second parameter (age, oxygen abundance, core rotation, mass loss on the RGB, etc.). Given that the previous section has demonstrated that a large intrinsic age range exists among the GCs, we will focus here on examining the hypothesis that age is the second parameter (Searle & Zinn 1978; Lee, Demarque, & Zinn 1994).

On the assumption that age is the second parameter, Zinn (1993) has divided the halo GCs into two groups, the old halo (OH) and younger halo (YH; these groupings are given in Table 2). GCs were deemed to be younger if their HB types were 0.4 redder [using the $(B-R)/(B+V+R)$ index; see footnote 3 in § 2.3] than the typical inner halo cluster at their metallicity. There are 25 OH clusters in our sample and 15 young halo clusters. Of the clusters that are clearly young in our sample, IC 4499, Rup 106, Pal 12, and Ter 7 are all part of the YH grouping. Only Arp 2 is incorrectly classified as an OH cluster. In addition, NGC 6652 has a a young $\Delta V_{\rm HB}^{\rm TO}$ age, even though it is classified as an OH cluster. This suggests that age is the dominant second parameter. Indeed, the YH clusters do tend to have lower ages than the OH clusters, as shown in Figure 3. However, incorrect classification of Arp 2 suggests that a third parameter affects the HB type of some clusters. Note that NGC 6652 ([Fe/H] $= -0.89$ and HB type $= -1.00$) lies at the boundary of the OH and YH clusters, so whether it belongs to the OH or YH group is uncertain.

The errors in our $\Delta V_{\rm HB}^{\rm TO}$ ages can be rather large; thus, for the bulk of the GCs, it is difficult to say with certainty that one particular GC is younger than another. This difficulty may be overcome by determining the weighted mean age of the OH and YH groups. The results of this calculation are shown in Table 5. If all of the halo clusters are included in the sample, then the YH is 2–4 Gyr younger than the OH

TABLE 5

MEAN AGES OF THE OLD AND YOUNGER HALO

M_v(RR Lyr)	Old Halo Age (Gyr)	Younger Halo Age (Gyr)	ΔAge (Gyr)	ΔAge/σ
All Halo Clusters				
0.17[Fe/H] + 0.79......	14.9 ± 0.3	11.6 ± 0.3	3.3 ± 0.4	7.5
0.20[Fe/H] + 0.98......	17.4 ± 0.4	14.2 ± 0.4	3.2 ± 0.5	6.2
0.15[Fe/H] + 0.98......	19.1 ± 0.4	15.3 ± 0.4	3.8 ± 0.6	6.6
0.15[Fe/H] + 0.72......	14.4 ± 0.3	10.8 ± 0.3	3.6 ± 0.4	8.3
0.20[Fe/H] + 1.06......	19.0 ± 0.4	15.7 ± 0.4	3.3 ± 0.6	5.9
0.20[Fe/H] + 0.82......	14.6 ± 0.3	11.6 ± 0.3	3.0 ± 0.4	7.0
0.25[Fe/H] + 1.14......	18.9 ± 0.4	15.9 ± 0.4	3.0 ± 0.6	5.4
0.25[Fe/H] + 0.91......	14.8 ± 0.3	12.2 ± 0.3	2.6 ± 0.4	6.0
0.30[Fe/H] + 1.22......	18.8 ± 0.4	16.2 ± 0.4	2.6 ± 0.5	4.8
0.30[Fe/H] + 1.01......	15.0 ± 0.3	12.7 ± 0.3	2.3 ± 0.4	5.3
Excluding Sgr Clusters				
0.17[Fe/H] + 0.79......	15.2 ± 0.3	13.0 ± 0.3	2.2 ± 0.5	4.6
0.20[Fe/H] + 0.98......	17.8 ± 0.4	15.3 ± 0.4	2.5 ± 0.5	4.5
0.15[Fe/H] + 0.98......	19.5 ± 0.4	16.7 ± 0.4	2.7 ± 0.6	4.5
0.15[Fe/H] + 0.72......	14.6 ± 0.3	12.5 ± 0.3	2.1 ± 0.5	4.6
0.20[Fe/H] + 1.06......	19.4 ± 0.4	16.7 ± 0.4	2.7 ± 0.6	4.5
0.20[Fe/H] + 0.82......	14.9 ± 0.3	12.8 ± 0.3	2.1 ± 0.5	4.6
0.25[Fe/H] + 1.14......	19.3 ± 0.4	16.7 ± 0.4	2.6 ± 0.6	4.4
0.25[Fe/H] + 0.91......	15.1 ± 0.3	13.0 ± 0.3	2.1 ± 0.5	4.6
0.30[Fe/H] + 1.22......	19.2 ± 0.4	16.8 ± 0.4	2.5 ± 0.6	4.3
0.30[Fe/H] + 1.01......	15.3 ± 0.3	13.2 ± 0.3	2.1 ± 0.5	4.5
Excluding Sgr and Very Young Clusters				
0.17[Fe/H] + 0.79......	15.2 ± 0.3	13.5 ± 0.4	1.7 ± 0.5	3.4
0.20[Fe/H] + 0.98......	17.8 ± 0.4	15.7 ± 0.4	2.0 ± 0.6	3.4
0.15[Fe/H] + 0.98......	19.5 ± 0.4	17.1 ± 0.5	2.3 ± 0.7	3.5
0.15[Fe/H] + 0.72......	14.6 ± 0.3	13.0 ± 0.4	1.7 ± 0.5	3.4
0.20[Fe/H] + 1.06......	19.4 ± 0.4	17.2 ± 0.5	2.2 ± 0.6	3.5
0.20[Fe/H] + 0.82......	14.9 ± 0.3	13.2 ± 0.4	1.7 ± 0.5	3.4
0.25[Fe/H] + 1.14......	19.3 ± 0.4	17.2 ± 0.5	2.1 ± 0.6	3.3
0.25[Fe/H] + 0.91......	15.1 ± 0.3	13.4 ± 0.4	1.7 ± 0.5	3.3
0.30[Fe/H] + 1.22......	19.2 ± 0.4	17.3 ± 0.5	2.0 ± 0.6	3.2
0.30[Fe/H] + 1.01......	15.3 ± 0.3	13.7 ± 0.4	1.6 ± 0.5	3.2

group, and the difference in age is significant at the 4.8–7.5 σ level. Perhaps more importantly, if the GCs are randomly sorted into two groups of the same size as the YH and OH groups, age differences as large as those found between the YH and OH groups occur only 0.5% of the time. Given the spread in ages found in the previous section, this latter test ensures that the differences in the mean ages of the two groups is not just a coincidence. If the Sgr clusters (Ter 7, Ter 8, and Arp 2) are removed, then an age difference of 2.5 Gyr is found significant at the 4.3–4.6 σ level. The chance of such a large age difference occurring in random subgroups is less than 0.5%. If, in addition to the Sgr clusters, all of the young clusters are excluded from the sample (IC 4499, Pal 12, Rup 106, and NGC 6652), then the difference in age drops to 1.6–2.3 Gyr (at the 3.2–3.5 σ level), depending on the choice of the M_v(RR) relation. The chance of such a large age difference occurring in random subgroups is less than 2.0%. Thus, we see that even when the obviously young clusters are removed from the sample, there is still a significant difference in the mean age of the OH and YH groups. Together, these results are consistent with the hypothesis that age is the second parameter and that a typical second parameter cluster is about 2–3 Gyr younger than the clusters that possess bluer HBs at similar metallicities.

Although our results are consistent with age being the second parameter, they cannot entirely rule out other phenomena. For example, we have assumed that the helium abundance is the same for all clusters of a given metallicity. If two clusters of the same metallicity have different helium abundances, it is possible to mimic the effects of a more youthful $\Delta V_{\rm HB}^{\rm TO}$ age while reddening the HB morphology.[4] Thus, our results cannot conclusively prove that age is the second parameter; they can prove only that our ages are consistent with age being the second parameter. However, we note that Lee et al. (1994) have extensively discussed arguments against parameters besides age being responsible for the second parameter. They found problems with every candidates second parameter except age. For example, variations in the helium abundance are ruled out by constraints set by RR Lyr periods.

As mentioned above, the second parameter is correlated with Galactocentric distance, but, as demonstrated by Figure 3 and discussed in the previous section, age is not correlated with Galactocentric distance in our data. This would appear to contradict the conclusion that age is the second parameter. This seeming contradiction may be resolved by a few factors: (1) there are a relatively small number of GCs in our sample coupled with the relatively large age errors (Lee et al. 1994 have 83 GCs in their HB sample); (2) some of our clusters are far from their apogalacticon, which tends to reduce the size of radial gradients; and (3) in the region $R_{\rm GC} = 8$–40 kpc, there is considerable scatter in the HB type–[Fe/H] correlation, with some clusters in this region having a similar HB type to clusters in the inner halo ($R_{\rm GC} = 8$ kpc). This is illustrated by the fact that beyond 8 kpc, our sample contains 13 OH clusters and 14 YH clusters. This suggests that while we should find a greater range of ages in the outer halo sample, the oldest clusters in the outer halo will have a similar age to the oldest clusters in the inner halo. Hence, one does not expect to find a strong age–Galactocentric distance relationship even if age is the second parameter. Instead, there should be a greater age range in the outer halo as compared to the inner halo. To test this hypothesis, the age range calculations discussed in the previous section were applied to the inner halo and outer halo sample. When all clusters were included, the probability of an age range existing was much higher in the outer halo sample as opposed to the inner halo sample. However, the age range of the inner halo sample was nearly the same as the outer halo sample [9.6 vs. 8.5 Gyr for our preferred M_v(RR) relation]. The determination of the age range of the inner clusters is rather uncertain, as there are only 13 clusters in this group, of which NGC 6652 is an obvious outlier. If it is removed from the inner halo sample, then there is no evidence for an age spread among the inner halo clusters. Hopefully, the question of an age–Galactocentric distance relation, and whether there is a difference in the range of ages found in the inner and outer halo, will be resolved by more high-quality data.

[4] This example was pointed out to us by the referee, Bruce Carney.

7. DISCUSSION

When we analyze our $\Delta V_{\rm HB}^{\rm TO}$ ages of 43 GCs (presented in Table 3), we draw the following conclusions: (1) if the slope of M_v(RR) with metallicity is less than 0.26, then an age-metallicity relationship exists, with the most metal-poor clusters being the oldest; (2) our data set does not contain strong evidence for an age–$R_{\rm GC}$ distance relationship; (3) independent of the choice of M_v(RR), there is strong evidence for an age spread of 5 Gyr among the bulk of the GCs; (4) about 10% of the GCs are substantially younger than the majority, and including them in the total sample increases the age range to about 9 Gyr; and (5) the mean age of the red HB, second parameter clusters is 2–3 Gyr younger than normal clusters, which is consistent with age being the second parameter. It would appear that conclusions (2) and (5) contradict each other, since the second parameter is correlated with Galactocentric distance (Searle & Zinn 1978; Lee et al. 1994). This contradiction may be resolved by noting that the errors in the age determinations are rather large ($\sim 10\%$); there is considerable scatter in the HB-$R_{\rm GC}$ relation; and there is weak evidence for an age–$R_{\rm GC}$ distance relationship (at the 94.5% confidence limit) in our data set.

In addition to the above, we note that the GCs Ter 7, Ter 8, and Arp 2 appear to be associated with the recently discovered Sgr dwarf spheroidal galaxy. This is based on the fact that the above objects are all located at similar distances and in the same region of the sky as Sgr (Ibata et al. 1994). In addition, these GCs have radial velocities similar to that of Sgr (Da Costa & Armandroff 1995). It appears that the Galaxy is in the process of accreting the Sgr dwarf and its accompanying GCs, two of which (Ter 7 and Arp 2) are anomalously young compared to the bulk of the GCs in the Galaxy.

The above conclusions strengthen the original proposal by Searle & Zinn (1978) that the outer halo of the Galaxy formed in a slow, rather chaotic collapse, with the Galaxy accreting material over several Gyr. The Sgr dwarf, and associated GCs, is an example of a large gas fragment that collapsed, self-enriched, and is now being accreted by the Galaxy. However, not all of the outer halo ($R_{\rm GC} > 8$ kpc) formed via *later* accretion. A significant fraction (50%) of the outer halo clusters in our sample do not have a strong second parameter effect and so are part of Zinn's (1993) old halo group. These old, outer halo objects were formed during the prompt collapse of the proto-Galactic cloud, though they still may have been accreted at a later time. As time passed, more metal-rich GCs formed and were accreted into the outer halo, leading to the observed age-metallicity relationship.

In contrast to our earlier work on the ages of 32 GCs (Chaboyer et al. 1992), the present GC sample contains no evidence that the inner halo formed in a rapid collapse (see Fig. 3). However, if NGC 6652 is removed from the sample, then there is *no evidence* for an intrinsic age range among the inner halo clusters, which would suggest that the inner halo did indeed form in a rapid collapse. In contrast, the conclusion that a large age range exists among the outer halo GCs is a robust statement. A more definitive answer on whether or not the inner halo formed in a rapid collapse requires more high-quality data of inner halo clusters.

We would like to thank the referee, B. Carney. His suggestions have lead to a substantially improved paper. In addition, R. Zinn provided us with useful comments on our initial draft. We are grateful to R. Zinn for providing us with a list of globular cluster groups and to Y.-W. Lee for allowing us to use his HB models, both in advance of publication. P. D. acknowledges partial support from NASA grants NAG5-1486 and NAG5-2795.

APPENDIX

ESTIMATING THE GAUSSIAN ERROR IN $\Delta V_{\rm HB}^{\rm TO}$

The errors in $\Delta V_{\rm HB}^{\rm TO}$ given in Table 2 are those quoted by the observers, who rarely specify how they have determined the error bar. For the statistical analysis that comprises the bulk of the paper, Gaussian 1 σ error bars are required. Perhaps the best way to estimate the Gaussian error in a measurement is to analyze repeated observations. In this vein, we have searched the literature for independent measurements of $\Delta V_{\rm HB}^{\rm TO}$ for which an error is also included. The results of our literature search are presented in Table 6, which gives the cluster name, $\Delta V_{\rm HB}^{\rm TO}$ value, and the reference. Using the $\Delta V_{\rm HB}^{\rm TO}$ values and errors, we have calculated and tabulated the quantity $\delta \equiv (\Delta V_a - \Delta V_b)/(\epsilon_a^2 + \epsilon_b^2)^{1/2}$, where ΔV_a is the measured $\Delta V_{\rm HB}^{\rm TO}$ with its error (ϵ_a) as reported by observer *a*, and ΔV_b and ϵ_b are the same quantities reported by observer *b*. Essentially, δ is simply the difference in the $\Delta V_{\rm HB}^{\rm TO}$ observations, normalized by the quoted errors. If the observers are quoting Gaussian 1 σ error bars, then δ should have a Gaussian distribution, with $\sigma = 1$. There are 17 measurements of δ in Table 6; for this sample size one would expect five values of δ in excess of 1 for Gaussian errors. However, this occurs only twice. This suggests that the reported errors are an overestimate of the Gaussian 1 σ error bars. Indeed, the *F*-test (Press et al. 1992) finds that there is only a 2% chance that δ has a standard deviation of 1.0. The quantity δ has an actual standard deviation of 0.61. Thus, multiplying the quoted errors by 0.61 yields the best estimate the Gaussian 1 σ error in $\Delta V_{\rm HB}^{\rm TO}$.

TABLE 6

INDEPENDENT $\Delta V_{\rm HB}^{\rm TO}$ OBSERVATIONS

Cluster	$\Delta V_{\rm HB}^{\rm TO}$	δ	References
NGC 104	3.61 ± 0.10	...	Table 2
	3.81 ± 0.18	−0.971	CSD
	3.76 ± 0.10	−1.060	SK
NGC 288	3.73 ± 0.12	...	Table 2
	3.70 ± 0.14	0.163	SK
	3.62 ± 0.10	0.704	Bergbush 1993, Pound et al. 1987
NGC 1261	3.57 ± 0.12	...	Table 2
	3.30 ± 0.14	0.379	Alcaino et al. 1992b
NGC 1851	3.45 ± 0.10	...	Table 2
	3.34 ± 0.10	0.778	CSD
NGC 3201	3.45 ± 0.21	...	Brewer et al. 1993
	3.44 ± 0.12	0.041	Alcaino et al. 1989, Cacciari 1984
NGC 4590	3.42 ± 0.10	...	Table 2
	3.49 ± 0.12	−0.448	CSD
	3.42 ± 0.10	0.000	Alcaino et al. 1990, Harris 1975
NGC 5897	3.60 ± 0.18	...	Table 2
	3.52 ± 0.14	0.351	Ferraro et al. 1992b
NGC 6121	3.68 ± 0.16	...	Table 2
	3.52 ± 0.10	0.848	SK
	3.45 ± 0.13	1.116	Kanatas et al. 1995
NGC 6171	3.75 ± 0.18	...	Table 2
	3.70 ± 0.11	0.237	Ferraro et al. 1991
NGC 6752	3.77 ± 0.16	...	Table 2
	3.72 ± 0.14	0.235	SK
NGC 6809	3.66 ± 0.10	...	Table 2
	3.54 ± 0.14	0.697	Alcaino et al. 1992a
NGC 7492	3.72 ± 0.14	...	Table 2
	3.61 ± 0.10	0.778	SK
Rup 106	3.32 ± 0.07	...	Table 2
	3.27 ± 0.12	0.360	CSD

Another estimate for the Gaussian 1 σ error in ΔV_{HB}^{TO} may be obtained by computing the standard deviation (using the small sample formulae of Keeping 1962) for each set of ΔV_{HB}^{TO} values given in Table 6. This standard deviation is then compared to the mean ΔV_{HB}^{TO} error quoted by the observers in Table 6. Dividing the standard deviation by the mean error and taking the average of this ratio yields 0.55. This is the amount by which one should multiply the quoted ΔV_{HB}^{TO} errors in order to obtain a Gaussian 1 σ error. This value is quite similar to the 0.61 obtained above. To be conservative, the value of 0.61 will be used.

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